NAIC-ID(RS)T-0321-96

NATIONAL AIR INTELLIGENCE CENTER

DEVELOPMENTS IN TRANSISTOR INFRARED DETECTORS

by

Gao Deping

19960903 016

Approved for public release: distribution unlimited

DTIC QUALITY INSPECTED 1

NAIC- ID(RS)T-0321-96

HUMAN TRANSLATION

NAIC-ID(RS)T-0321-96 24 July 1996

MICROFICHE NR:

DEVELOPMENTS IN TRANSISTOR INFRARED DETECTORS

By: Gao Deping

English pages: 15

Source: Cama, China Astronautics and Missilery Abstracts, Vol. 3, Nr. 1, 1996; pp. 101-106

Country of origin: China
Translated by: Leo Kanner Associates
F33657-88-D-2188
Requester: NAIC/TASC/Richard A. Peden, Jr.
Approved for public release: distribution unlimited.

THIS TRANSLATION IS A RENDITION OF THE ORIGINAL FOREIGN TEXT WITHOUT ANY ANALYTICAL OR EDITORIAL COMMENT STATEMENTS OR THEORIES ADVOCATED OR IMPLIED ARE THOSE OF THE SOURCE AND DO NOT NECESSARILY REFLECT THE POSITION OR OPINION OF THE NATIONAL AIR INTELLIGENCE CENTER.	PREPARED BY: TRANSLATION SERVICES NATIONAL AIR INTELLIGENCE CENTER WPAFB, OHIO

GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

NAIC-ID(RS)T0321-96

DEVELOPMENTS IN TRANSISTOR INFRARED DETECTORS

BY: Gao Deping
(Loyang Institute of Tracking and Communications Technology)

ABSTRACT

This article primarily introduces developmental trends in resistor infrared (IR) detector technology which includes HgCdTe optoelectronic diodes, Shottky-barrier light emitters, and GaAs/AlGaAs inter sub-band quantum trap optoelectronic conductors. The development of these IR devices are aimed at improving element and component capability, the manufacture of large electronic sweep arrays, increasing operational temperatures, reducing cost and making application easier. In addition, this article also compares the capabilities of different models of HgCdTe devices.

1. Forward

The appearance of large electronic sweep infrared focal plan arrays (IR FPA) are the newest achievement in the field of infrared detectors. Because focal plane arrays increase detection sensitivity and make the infrared system more simple, they have important applications in military and civilian fields. In many infrared detectors, HgCdTe is used as a type of eigenphoton detector, having a high coefficient of light absorbance and quantum efficiency. Compared to non-intrinsic devices and silicate Shottky-barriers, they generate less heat, so they are an important type of infrared detector in the 1-25μm light spectrum. The intrinsic detector discussed in this chapter has an operating temperature higher than other models of photon detectors.

Although HgCdTe can operate on the short wave infrared, medium wave infrared and long wave infrared bandwidths, it is faced with a large group of technical problems in batch production just like other transistor materials. The primary problem is that the toxic components comprise a health hazard, and it is difficult to grow large crystals and extension layers with an even composition. At the present most of these problems have already been overcome, and the quality of materials and devices has already been improved. However, because of stability problems with the crystal lattice, surface and boundaries, there are still problems, so other materials will have to be considered if the properties of the devices are to be improved.

Devices recently developed can be divided into three categories:

1). Free carrier detectors-metallic silicate Shottky barriers.

2). New three metal alloy intrinsic detectors to replace HgCdTe, such as AsSb, HgZnTe, and HgMnTe.

3). Quantum trap (QW) infrared detectors.

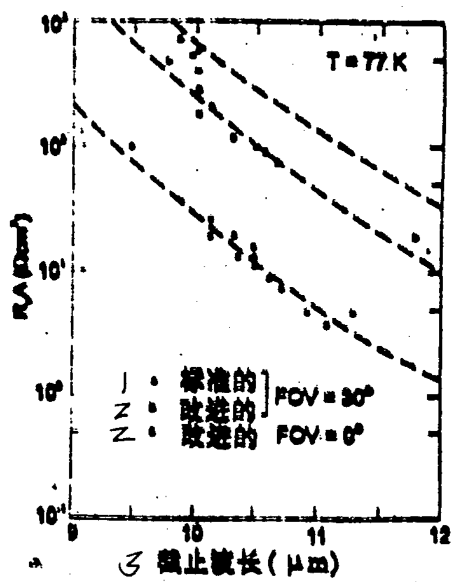
Due to limitations in space, this article will only provide a brief introduction to the development of the technology of HgCdTe and to category one and three detectors.

2. HgCdTe optoelectronic diodes

Currently, composite HgCdTe focal plane array design is based on junction optoelectronic diodes. The advantages of these are that they are low energy, and directly matched with silicon CCD input levels their impedance is high, with no strict noise requirements for readout devices and circuitry. For present-day HgCdTe optoelectronic diodes, ions are usually injected in **p** model

materials, forming **n^+-p junctions. However, ordinary** p material have a fairly capture density, and through the Shockley-Read-Hall complex mechanism, capture density controls the life of the residual carrier. When the temperature is below 60K, this type of optoelectronic diode capability carrier mechanism comes under the control of some defect for unknown reasons.

Fig. 1. Improved n-on-p plane HgCdTe homogeneous at 78K



1. Standard. 2. Improved. 3. Cut-off wavelength (μm).

At temperatures below 77K, the LWIR n^+-p model HgCdTe optoelectronic diode dark current control is usually controlled by the assisted capture by the barrier crossing. Recently the technology has been improved, greatly improving the properties of the plane n-on-p HgCdTe homogeneous detectors. This is done by injecting ions into a HgCdTe liquid phase extension (LPE) 8-12μm above a CdZnTe substrate. This causes a level of magnitude improvement of the R_oA (when the cut-off wavelength is λ_c**=10μ**, it is between 400-750Ωcm^2). This is because within the p model

material base region, the life of a small number of carriers is increased and the p model extension layer becomes thinner. Figure 1 shows the graph of R_oA and the cut-off wave length in the old technology. The dotted line is the theoretical curve.

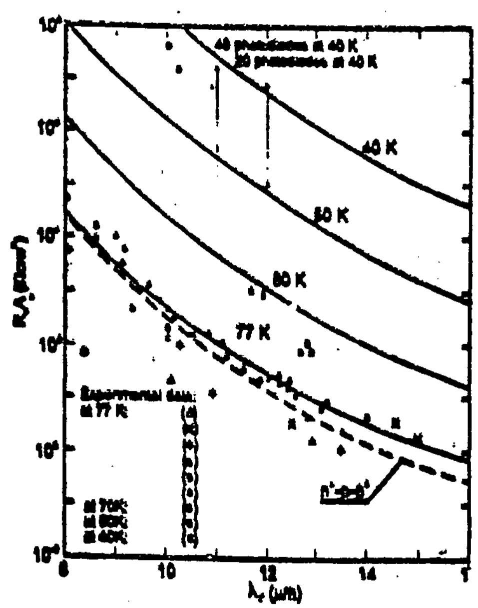
In 1985 Rogalski and other pointed out that for the p^+-n model structure, the n model zone is thicker and the hole mobility is lower, and as a result, the R_oA accumulation is greater than the n^+-p model. This hypothesis has been experimentally demonstrated with a p$\pm$n model HgCdTe structure. A major advantage of p-on-n devices is that the n model HgCdTe carrier concentration can be very easily controlled through doping to within the 10^{14}-$10^{5}cm^{-3}$ range, and in n-on-p devices, it is very difficult to attain this level in the p model carrier control. This is because in the n model HgCdTe material the carrier concentration is even lower, so the life of its minority carrier is even longer than in the p model base region.

There have been experiments which have demonstrated that p-on-n and n-on-p model diodes at 77K and $\lambda_c<10\mu m$, R_oA accumulation is about the same, and when $\lambda_c>10\mu$, the R_oA accumulation of the n-on-p model diode is generally not so good, its quantum efficiency is lower, tending toward higher impedance. This could be because the manufacturing technology of the n-on-p heterogeneous structure is not yet mature.

Recently, Rogalski and other analyzed the properties of the P^+-n-n^+ HgCdTe homogeneous diode (base zone 20 μm thick). The effects of the properties of doping distribution on the properties of the optoelectronic diode (R_oA accumulation and quantum efficiency) were solved through forward conditional stability analysis. Figure 2 shows the relationship between the R_oA accumulation and the cut-off wave length of p^+-n-nl^+ LWIR HgCdTe

optoelectronic diodes at different temperatures. For the purpose of comparison, this figure also shows the theoretical curve of a n^+-p-p^+ optoelectronic diode at 77K (at the P model base region, the optimum concentration is Na=10^{18}cm^{-2}.). We can see from this figure that np-p^+ is not quite as good as the p^+-n-n^+ structure, especially at the long wave regions. We can also see that a number of experimental data conform very well to the theoretical curve (60-77K), especially at 77K, 7μm<λ_c,10μm. When the temperature drops, the conformity is not so good. This is probably because no consideration has been given to the additional carriers in the structure (such as tunnel current and surface leak current).

Fig. 2. LWIP p^+-n-n^+ HgCdTe optoelectronic diode at 77K
Curve of R_A vs. cut-off wavelength



So far, photovoltaic HgCdTe focal plane arrays have primarily been based on p model materials. Linear arrays (240, 288, 480, and 960 elements), two dimensional arrays have time delay integrated

(TDI) sweep arrays, and two dimensional fixed arrays have reached 480 X 640 elements, with image element dimensions from 20μm square to 1mm^2. The best composite structures can independently optimize material doping, detector manufacturing processes and signal processing circuits.

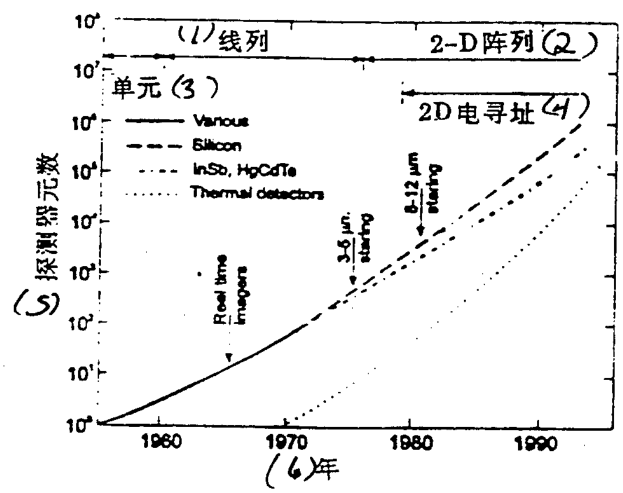
Currently, HgCdTe focal plane array properties are restricted in uniformity. At 77K, p-on-n plane heterogeneous structures grown with MBE and which are controlled by R_oA integration distribution factors have a controllability of $\geq$ 95%, and at 40K it is 70-80% (limited by the number of moving ions). This dispersion of R_oA limits the application of HgCdTe focal plane arrays with low background additions.

CdTe and CdZnTe are the most widely used substrate materials for backward radiation HgCdTe detectors, because these can be used to grow low defect density HgCdTe extension layers. However, there are fairly few of these useable substrate, and they are expensive and easily damaged, and a thermal expansion mismatch can easily occur between the extension layer and the silicon. When the composite model focal plane array is cooled to 77-120K, a lateral displacement can easily occur between the detector and the read-out substrate. Therefore, detectors made using this type of substrate have a maximum number of 128 X 128 elements. In order to produce large and cheap composite focal plane arrays, it is necessary to replace these with other detector substrate. A manufacturing process of Rockwell called PACE-1 uses a fairly cheap sapphire substrate, which is used to manufacture a larger focal plane array with a mismatch rate 40 percent lower than CdTd. Table 1 lists properties of the PACE-1 HgCdTe focal plane arrays. We can learn from this table that for 640 X 480 focal plane arrays produced using this process, NEΔT=0.015K. This is one order of magnitude higher in sensitivity than the typical PtSi 640 X 480 focal plane

array currently in common use. However, the infrared absorption of sapphire limits the use of this type of focal plane array to wavelengths in excess of 5.5μm. An 8-14μm LWIR detector has already been made using a GaAs substrate. However, the dimensions are also limited. Figure 3 shows the development over time of this type of focal plane array in the 3-5μm and 8-14μm bands.

Recently several laboratories have begun to use silicon substrate to manufacture HgCdTe detector arrays. This type of substrate has the same coefficient of thermal expansion as the silicon read-out circuit. The large PACE-3 640 X 480 focal plane array is one of these. These new large plane array HgCdTe have an average R_oA of up to $1.78\times10^8\Omega cm^2$, λ_c=9.0μm (f/2 field of vision, 300K background).

Fig. 3. Growth in size of detector arrays over time



1. Linear array. 2. Two dimensional array. 3. Single element. 4. Two dimensional electrical addressing. 5. Number of detector elements. 6. Year.

Table 1.

Parameter	256X256	640x640
Image element spacing	40	27
Core chip seal (LLCC)	68 pin	84 pin
Typical useable DR (10^8)	>10	>5
MWIR NETD,Qh=$3X10^{14}cm^2s$ (mk)	<7	<15
Nonuniformity of response (max-min)	<1.4:1	TBD
Image element operability	>98	TBD
Output	(2)	4
Max data rate of each output (MHz)	20	20
Minimum detection rate Qh=$3X10^{14}/cm^2s$	>5	>5
($10^{22}cmHz^{1/2}W^{-1}$) conversion ratio (Nv/e)	46	35

3. Light emission detectors

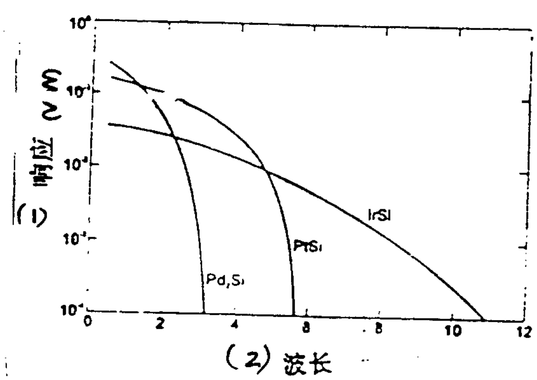
In 1973 Shepherd and Yang proposed a silicon Shottky-barrier detector focal plane array which could be produced in large scale and could replace the HgCdTe focal plane device for thermal imaging. At first, detection and read-out was done in a chip, and the read-out circuit was extremely complex. Later, because of continuous development of Shottky-barrier technology, it is now possible to use them to make the largest infrared imaging detector arrays.

The greatest advantage of the Shottky infrared detector is that it responds to a wavelength of 3-5μm. Radiation penetrates the P-model silicon and is absorbed in the metallic PtSi, generating a thermal hole, and then penetrating the barrier to enter the silicon zone, causing the silicate to have a negative charge. The different detection mechanism forms the unique characteristic of the Shottky-barrier detector. The Shottky light radiation is not to related to the transistor doping, the minimum carrier life or the alloy composition. Therefore, it has the advantage of spacial uniformity. The uniformity is only restricted by the geometry of the detector. At the atmospheric window at 3-

5μm its effective quantum efficiency is very low, only about one percent, but in focal plane arrays using almost total frame integration methods, it is possible to obtain useable sensitivity.

Figure 4 shows the relationship between response and wavelength of three different Shottky-barrier detectors. We can see that IrSi Shottky-barrier detectors have a response that can be extended to the long wave infrared zone, but must be cooled to below 77K.

Fig. 4. Spectrum response of PdSi, PtSi and IrSi Shottky-barrier detectors



1. Response. 2. Wavelength.

Table 2. Growth of Shottky-barrier FPA technology

1 阵列大小	2 型号	3 象元尺寸(μm²)	4 年代	5 填充系数(%)	6 公司
25×25	IL-CCD	160×80	1978	17	RADC
320×244	IL-CCD	40×40	1988	43	Sarnoff
640×488	IL-CCD	21×21	1991	40	NEC
1040×1040	CSD	17×17	1991	53	Mitsubishi

1. Size of array. 2. Model number. 3. Size of image elements (μm). 4. Year. 5. Activity coefficient. 6. Corporation

The technology of Shottky-barrier focal plane arrays has grown very quickly (see Table 2), with the size of the Shottky-barrier focal plane array doubling about every 18 months. The first Shottky-barrier focal plane array was a 25 x 50 element IRCCD. At the time, because the PtSi layer was fairly thick, the response was very low. By reducing the thickness of the PtSi, quantum efficiency has been greatly improved. The PtSi layer has been reduced to 2nm. Another method of improving response is structural design of the optical cavity, with a 1024 X 1024 imaging sensor not being used. The dimensions of the imaging elements of this array are now down to 17 X 17μm (in two dimensional focal plane arrays), with an activity coefficient of 53 percent. The response of the sensors is directly proportional to their activity coefficient (ratio of imaging element dimensions to detector area). Improving the activity coefficient is most important in the development of Shottky-barrier infrared sensors. It involves the read-out structure, array structure and detector structure. Although the interlinear shift CCD (IL-CCD) structure is widely used in solid state imaging devices, it is difficult to design small imaging elements and high activity coefficient array detectors for this structure. The IL-CCD activity coefficient is generally between 20 and 30 percent.

In 1987 charge scanning devices (CSD) were used to make the first Shottky-barrier infrared imaging sensor with television resolution. The CSD read-out structure is very attractive because it can both increase the activity coefficient as well reduce the degree of saturation of the sensors. Recently the CSD structure was used in a chip to develop a 1040 X 1040 array with NETD=0.1k (f/1.2 optical system). Mitsubishi Research also used the CSD structure to improve a 512 X 512 imaging sensor, with NETD estimated at 0.033K (using an f/1.2 optical system, and 300K background).

Recently, developments in MBE technology has permitted the manufacture of a high quality GeSi film on a silicon substrate, using GeSi/Si heterogeneous structure diode internal light emitter in infrared detection. In 1990 the first GeSi/Si heterogeneous structure detector was made, with a light spectrum response of 2-12μm and a quantum efficiency of three to five percent. Also, the λ_c of this type of detector can be controlled by the percentage of Ge in the SiGe composition. A CCD readout 400 X 400 GeSi/Si heterogeneous array was recently manufactured which can operate at 53K, λ_c=9.3μm, NEΔT-0.2K (f/2.35), and nonuniformity of response of less than one percent. Although this type of device is still in the early stages of development, its capabilities already exceed those of the IrSi detectors with the same λ_c and quantum efficiency. Quantum efficiency can be improved by increasing absorption and internal photon emission efficiency through combining optimum SiGe thickness and light cavity structure.

4. Inter Sub-band GaAs/AlGaAs QWIR detectors

Due to the appearance of molecular beginning extension (MBE) technology first proposed by E. Saki and Tsu, there has been continued increased interest in transistor super lattice (SL) and quantum tap structures. The characteristics of this type of device are: it can use inter band processing, it can use chemically stable wideband gap materials. Therefore, it can use such materials as GaAs/AlGaAs, InGaAs/InAlAs, InAs/GaInSb, SiGe/Si and others. QWIR detectors with response of 3-13μm have already been verified.

The more familiar of the QWIR detectors is the GaAs/AlGaAs multi quantum trap detector. Major improvements have been made in its capabilities and detection sensitivity, with 128 X 128 and 256 X 256 focal plane arrays already manufactured. Their infrared

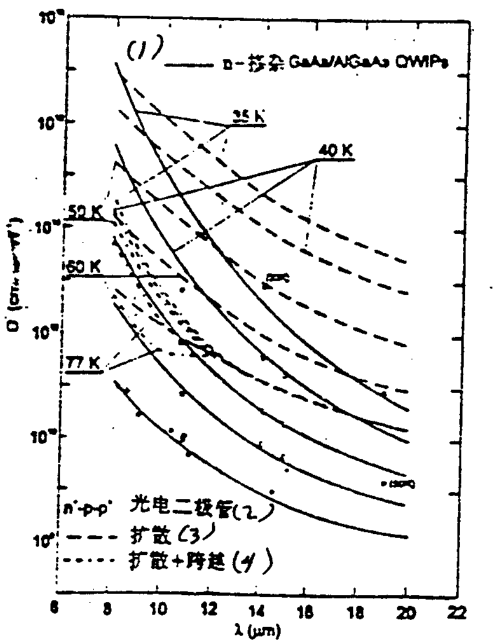
imaging properties are comparable to HgCdTe devices using the same advanced processes. Compared to HgCdTe, the GaAs/AlGaAs quantum trap devices have a number of advantages, including the ability of using the mature technology of growing GaAs crystals, production using standard manufacturing processes, and growing MBE on GaAs crystals with very high uniformity and good control, high rate of products meeting specifications, low cost, better stability and the sturdiness of their inherent radiation.

There have been comparisons of single GaAs/AlGaAs multiple quantum trap infrared detectors and λ_c=i.3μ and 10μm ideal HgCdTe photoconductive controllers which have lead to the discovery that within the range of temperatures of 40 to 100K, the GaAs/AlGaAs SL heat generation rate was five orders of magnitude higher. Furthermore, the advantages of HgCdTe is the longer carrier life. In a single SL, the restricted carrier moves freely within this plane. The recurrence rate of this type of carrier is extremely high.

However, among photoconductors, the HgCdTe photodiode is attractive because it is low power and because its direct matching high impedance to the output level of the SiCCD in two dimensional composite focal plane arrays. However, because the product quality is low, large photovoltaic HgCdTe focal plane array are still very expensive. This low percentage of products which meet specifications is caused by high rate at which electron activity defects occur, resulting in long wave infrared HgCdTe devices sensitive to defects and surface leaks. This is determined by the basic characteristics of the materials. However, GaAs/AlGaAs has the advantage of uniformity, as well the advantages of controllability and high rate of acceptable products. This is very important for the production of large area array devices.

There is only a weak correlation between GaAs/AlGaAs quantum trap infrared photoconductors (QWIP) detection rates and the doping concentration and the biased voltage. Figure 5 shows the curve of the detection rate and the cut-off wavelength at different temperatures. We can see from this figure that there is very good conformity between the theoretically calculated curve and the experimental data ($8\mu m \le \lambda_c \le 19\mu m$, $35k \le T \le 77k$). This figure also compares the GaAs/AlGaAs QWIP detection rate with the theoretic limits of the n^+-p-p^+ HgCdTe optoelectronic diode. We can see that when $\lambda_c = 8\mu m$ and at 40K, the two detectors have about the same detection rate. When the temperature is lower, the QWIP have somewhat better properties, and within the range of even longer cut-off wavelengths, the HgCdTe detection rate is even higher. This superiority becomes more marked as the cut-off wavelengths become longer.

Fig. 5. Relationship between detection rate and cut-off wavelength at 77K of the GaAs/AlGaAs QWIP and the n^+-p-p^+ HgCdTe optoelectronic diode.



1. Doped GaAs/AlGaAs QWIP. 2. n^+-p-p^+ optoelectronic diode. 3. Dispersion. 4. Dispersion plus skipping.

5. Conclusions

HgCdTe alloys are important materials for high capability, high speed elements and small array infrared detectors. They are widely used in high capability infrared imaging. However, there has recently been a trend toward gradually replacing them with narrow band mercury transistor HgZnTe, especially in applications requiring high stability. Shottky-barrier array devices have occupied the prominent position in high resolution applications between 3-5μm. GaAs/AlGaAs quantum trap infrared photoconductor (QWIP) arrays will play a major role in low background long wavelength applications.

At the present time infrared transistor imaging systems require low temperature cooling and the optical systems are complex and the materials are expensive. Therefore, applications are limited to a number of key areas. There continue to be advances in the development of low-cost, non-cooled imaging systems. These systems use thermoelectric detectors or thermal resistance radiation detectors (bolometer). This type of system will reduce the cost of high capability thermal imaging devices by two orders of magnitude, and will become widely used within the next ten years.

It is predicted that the low temperature growth of HgCdTe on silicon circuit substrates can exceed the physical limitations and stringent cooling requirements of Shottky-barrier devices. There will be no problems using narrow band-gap intrinsic semiconductors operating in a state of non-equilibrium in high detection rate, high speed elements and devices and small array infrared systems. The future of the quantum trap (QW) structure and the super lattice is not very clear.

(Bibliography omitted in original text.)